Studies on Convection in Polar Oceans

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LONG-TERM GOALS

The long-term goal of our research program is to identify fundamental hydrodynamical processes related to polar oceanography and to study them in-depth using laboratory, theoretical and numerical modeling.

OBJECTIVES

The objective of the work being reported was to investigate fundamental physical processes related to deep-ocean and under-ice convection occurring in high latitude oceans. With regard to deep convection, the aspects of interest were the preconditioning of a stratified region prior to the onset of convection, breakdown of stratification leading to turbulent convection, growth of convective layer against stable stratification, scales of convection, lateral processes leading to horizontal buoyancy exchanges and the final collapse of deep-convective regions. Studies on convection under an ice cap included the formation and melting of ice due to surface cooling of a two-layer stratified fluid. This problem is rich in a variety of physical processes such as double-diffusive transports of heat and salt and turbulent mixing across the pycnocline that separates the two layers. Important new mechanisms related to above-described processes were delineated and simple parameterizations were proposed to represent convective events in numerical models.

APPROACH

Laboratory modeling and accompanying theoretical analyses are the key approaches used in our studies. Experiments on turbulent convection were conducted by heating the bottom boundary of a wide, linearly (temperature) stratified fluid container placed on a rotating table. The time evolution of the turbulent convective layer and the properties of turbulence were studied using a series of thermistor probes and conventional particle tracking velocimetry. The flow configuration for the experiments on ice formation consisted of a layer of cold, salty water overlaying a relatively deep bottom layer of warm, saltier water. The experiments were conducted in an insulated tank placed in a walk-in freezer. A system of thermocouples was used to measure the temperatures at fixed levels in water, ice and ambient air. Microscale conductivity and temperature probes were used to obtain vertical profiles of temperature and salinity in water.

WORK COMPLETED

Laboratory experiments and associated theoretical analyses on (i) the development of turbulent convection in stratified fluids in the presence of background rotation and (ii) the ice formation/melting in two-layer fluids due to surface cooling were completed.

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RESULTS

In the studies of turbulent convection in rotating and stratified fluids, it was shown that the growth of the convective mixed-layer is dynamically affected by background rotation (or by Coriolis forces) when the parameter $R = (h^2\Omega^3/q_0)^{2/3}$ exceeds a critical value, R_1, which is approximately 100. Here h is the depth of the convective layer, Ω is the rate of rotation and q_0 is the buoyancy flux at the bottom boundary. When $R > R_2$, where R_2 is approximately 300, the buoyancy gradient in the mixed-layer was profoundly affected by background rotation (Figure 1). Conversely, when $R < R_1$, the buoyancy gradient in the convective layer is independent of the rate of rotation and approaches that of convection in non-rotating fluids. When $R > R_2$, the entrainment velocity was found to be dependent on the buoyancy frequency of the overlying stratified layer, the rate of rotation and the conventional (Deardorff) convection velocity. A simple theoretical formulation for the rate of entrainment was derived, which was found to be in good agreement with the experimental results. The results also indicate that entrainment in this case is dominated by non-penetrative convection and the entrainment interface is characterized by small-scale vortices penetrating into the non-turbulent layer above (Figure 2).
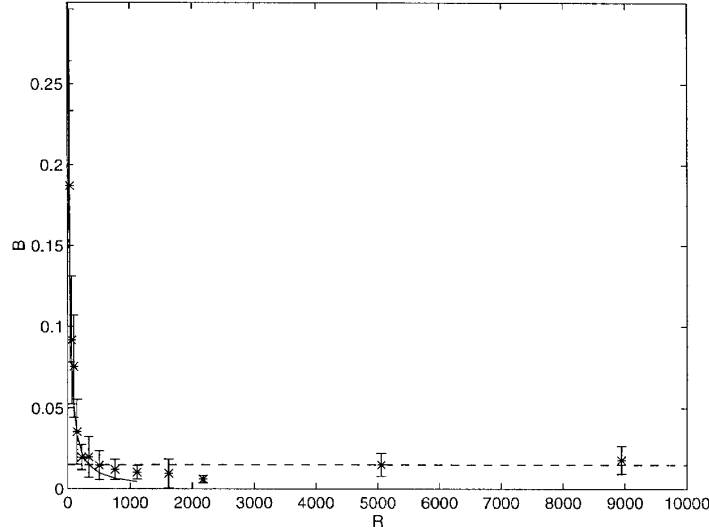

Figure 1: Non-dimensional mean buoyancy gradient B (normalized by $\oslash^2$) in the convective layer as a function of R. Note the transition from $B \sim R^{-1}$ regime to B = 0.02 (constant) regime, signifying the onset of rotational effects in the convective layer.

The two-layer flow configuration used for ice formation/melting studies, in general, should enhance its static stability when external fluxes of heat and salt are absent, i.e., the net density difference between upper and lower layers increases with time. When external fluxes of heat (because of surface cooling) and salt (rejected during ice formation) are applied, however, this fluid system was found to become unstable, leading to vertical overturning of fluid layers. The heat advection from the warmer bottom layer to the colder upper layer, associated with overturning, was found to be crucial in determining the response of ice sheet to the overturning event. For example, abrupt melting of the entire or a major part of the ice sheet is possible under some conditions. Descriptions of salient physical processes pertinent to the evolution of the ice-water system were advanced using fundamental concepts of fluid mechanics, and quantitative measurements were compared with the predictions of a theoretical model developed to explicate the flow evolution.
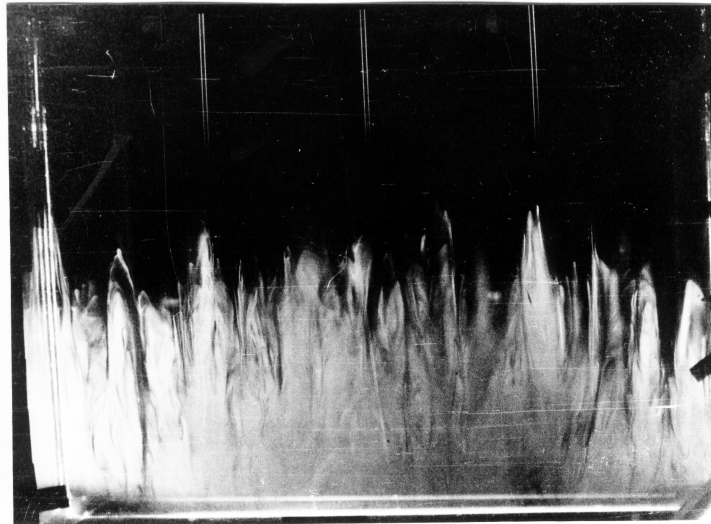
Figure 2: A photograph showing the entrainment interface that separates the bottom convecting layer (colored with dye) from the linearly stratified layer (dark) aloft. Note the penetration of small-scale vortices into the top layer.

IMPACT/APPLICATIONS

The study on rotating convection in stratified fluids delineated a criterion to quantify the effects of rotation on deep convection in high-latitude oceans. Application of our results to the data obtained during the Labrador Sea deep-convection experiment indicates that laboratory experiments can establish a useful framework to interpret field measurements. Some of the successful laboratory-based predictions in this context were the generation of dynamically significant buoyancy gradients in deep convective layers and the penetration of lagrangian floats beyond base of the turbulent mixed layer (D'Asaro 1996). The parameterizations established in our ice-formation work will be of immense utility in future ice-modeling work related to polar oceans. The phenomena observed during our experiments will also be helpful in interpreting field observations, such as those related to the "freeze-melting" phenomenon.

TRANSITIONS

Our laboratory experimental work on rotating convection is being used for calibration of numerical models by several researchers, including John Marshall's group at MIT (Marshall & Schott 1998), William Lavelle's group at Pacific Marine Environmental Laboratories (Lavelle & Smith 1996) and Roland Garwood's group at the Naval Post Graduate School. Parameterizations based on our experiments are being currently used by Eric D'Asaro's group to interpret some of the lagrangian float trajectories observed during the Labrador-sea convection experiment.

RELATED PROJECTS

The PI is working closely with Dr. David Smith IV in an ONR project dealing with numerical simulation of multiple leads and parameterization of air-sea exchanges through leads..

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